ATLAS Trigger: design and commissioning

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Abstract. The ATLAS detector at CERN's Large Hadron Collider (LHC) will be exposed to proton-proton collisions from beams crossing at 40 MHz. A three-level trigger system was designed to select potentially interesting events and reduce the incoming rate to 100-200 Hz. The first trigger level is implemented in custom-built electronics, the second and third trigger levels are realized in software. The trigger system and its design parameters will be described with focus on computing and data acquision challenges. The results from both commissioning cosmic runs and first experiences from the LHC beam in 2008 will be overviewed. These running periods allowed us to exercise the trigger system online, including its configuration and monitoring infrastructure, as well as reconstruction and selection algorithms. The details on the plans for commissioning the ATLAS trigger when the LHC starts operations will be presented.

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INTRODUCTION

The Large Hadron Collider (LHC) will collide protons at a center of mass energy of 14 TeV, allowing to probe the Standard Model at an unprecedented energy scale and enabling opportunities for discovering new physics beyond the Standard Model. The LHC design luminosity, 10^{34} cm^{-2}s^{-1} will provide large enough event samples, about 100 fb^{-1}/year, to ATLAS, one of the experiments dedicated to these studies. The initial running conditions will be far from these values, starting with 3.5 TeV beam energy and rising to 5 TeV per beam with much lower luminosity, so the experiments need to be prepared for different machine scenarios from the beginning. At the design luminosity, beam bunches colliding at a rate of 40 MHz lead to an average of 23 collisions per crossing, which yields about 1 GHz of p-p interaction rate. Among these, the interesting physics is represented with different production rates: for example we expect about 1 kHz of beauty quarks, 100 Hz from W/Z gauge bosons, 10 Hz from top quarks events and 0.1 Hz from light Higgs bosons, going down to 10^{-6} or lower for heavy Higgses. They compete with inelastic background events occurring at 1 GHz and with QCD jets at 1 kHz with transverse jet energies above 100 GeV. Since these rates are predicted by extrapolating the Tevatron measurements to these energy scale, large uncertainties must be considered. The ATLAS trigger system [1] must be able to select interesting events, reducing the rate of events to be analyzed equal to the number affordable by the available computing budget and storage capability. To fulfill the stringent request on the rate reduction, almost 5 orders of magnitude rejection power, the trigger system is organized in three levels, in which the first level based on custom-build electronics reduces the input rate to the computer farms that represent the High Level Trigger (HLT). The trigger selection is based on inclusive signatures with high transverse momentum (p_T). This allows to select events originated by hard scattering processes, among those from soft QCD interactions, and equally both ensuring the required samples for studies on Standard Model physics, in overlap with Tevatron, and being sensitive to un/predicted new physics. Reasonable safety factors must be included to account for uncertainties given by physics, cross-sections and background estimations, and depending on the detector performance. During the starting phase of the LHC machine, the trigger must include signatures for the detector commissioning, while during stable running, the same can be used for monitoring, calibration and energy scale determination, and to allow the measurement of detectors and trigger efficiency from data.

Trigger architecture

Three main principles drove the design of the ATLAS trigger system. Firstly, ATLAS chose a three-level architecture in order to reduce the dataflow requirements, and exploited the Region-of-Interest (RoI) approach at the second-level trigger. The dataflow and the trigger architecture are strictly correlated and based on local readout buffers and on the complex communication between different elements. A second requirement on the trigger system is the redundancy of

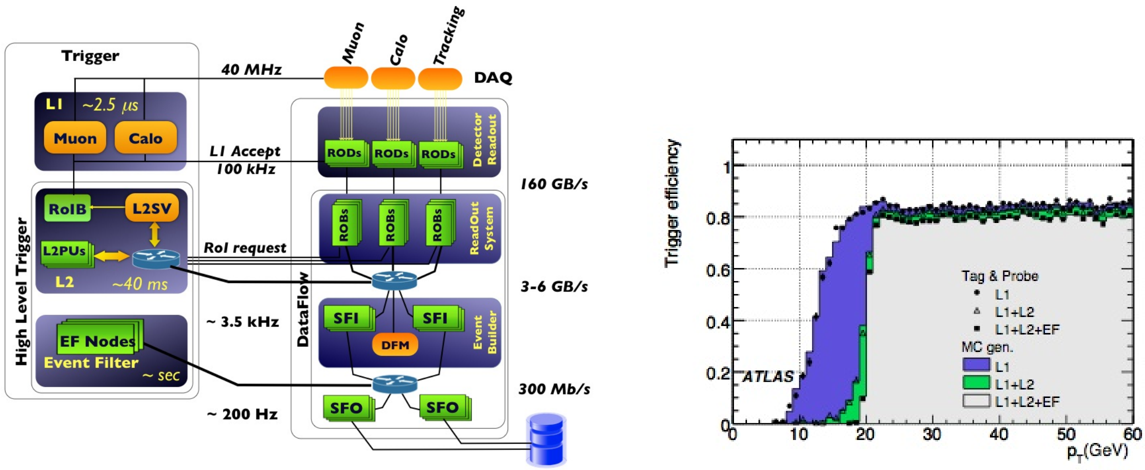

FIGURE 1. Left (a): Schematics of the ATLAS trigger architecture, showing all the elements and their main characteristics: for each trigger level the corresponding latency, sustained rate and dataflow throughput are shown. The expected event size is 1.5 MB. Right (b): Muon trigger efficiency turn-on curve after each trigger level determined both by the tag-and-probe method and by using the Monte Carlo generator as a reference, in the high-luminosity scenario (1000 pb^{-1}).

the selection criteria, which ensure high trigger efficiency and gives the possibility to measure it from the data. For this purpose the so-called "Trigger Menus" are used, which are combinations of event signatures which are tested by the trigger system and follow the trigger strategy described in the next sections. The latest request on the trigger system is the flexibility, so that all the possible variations of the LHC conditions can be faced up. This is of particular interest if we consider that changes in the luminosity can vary the event characteristics, since the number of p-p interactions per bunch-crossing depends on it.

The different components of the trigger/dataflow system are shown in Fig. 1.a. Within the first-level trigger, coarse granularity muon or calorimeter objects are identified by dedicated fast detectors and custom electronics working at 40 MHz machine clock rate and used to reach a rate reduction of O(10^3). The level-1 system uniquely identifies the correct LHC bunch crossing (BC) and the geometrical Region of Interest containing the interesting objects. Only the data contained in the selected region is further analyzed in the subsequent level-2 system. The latter has access to full granularity information and to the tracking systems information and uses custom algorithms optimized for timing performance (40 ms latency). The data volume transferred to the level-2 farms is about 2% of the full event size (about 1.6 RoI per event on average). The full event is available after the Event Builder, when the third level trigger, called Event Filter, can select events after performing event reconstruction, using the same algorithms, geometry and calibration constants also available offline. Level-2 and Event Filter share the same software infrastructure, implemented on Linux PC farms, and are usually referred as High Level Trigger. To further reduce decision latency and network traffic the reconstruction at each level is seeded by the previous one and steps of feature extraction are alternated to hypothesis testing, so that events can be rejected at any step with optimized algorithm scheduling, as soon as possible.

Muon trigger. Dedicated trigger detectors (TGC in the endcap regions $|\eta| > 1.05$ and RPC in the barrel) provide the first-level trigger and profit from their optimal timing resolution (RPC time resolution is around 2 ns) to detect muons and assign a p_T threshold based on the track deviation in the toroidal field. Trigger algorithms run on both bending and non bending planes to further reject fake muons induced by noise and physics background in the air-toroid structure. The muon system allows for B-physics studies with a wide range of p_T selection (from 4 to 40 GeV), with the low momentum muons giving the most relevant contribution to the level-1 rate. The HLT algorithms combine tracks in the Muon Spectrometer and in the Inner Detectors and separate muons from jets with isolation criteria based on energy deposit in the calorimeters.

Calorimeter trigger. With about 7200 projective trigger towers and acceptance coverage up to $|\eta| = 4.9$, calorimeter level-1 trigger relies on various combinations of cluster sums and isolation criteria able to identify trigger objects like electrons/γ, τ, jets, missing E_T and the global scalar E_T. Dedicated processors apply the algorithms, using programmable E_T thresholds on look-up-tables, identify the BC with peak finders and find the clusters with the sliding window technique. The HLT uses more topological variables and tracking information for electrons from Inner Detectors. Isolation criteria can be imposed to distinguish electrons from QCD jets or photon conversion to electron/positron pairs.

Expected trigger performance. In [2] the reader can find a detailed descriptions of the performance of the ATLAS trigger, as measured with samples of simulated signal events. The trigger efficiency is calculated with respect to the offline reconstruction. The expected performance of each trigger selection is described by the so-called "turn-on" curves, in which the trigger efficiency is shown as a function of the applied threshold. The slope of the curve at the effective threshold reflects the finite p_T resolution expected from design. The dependency on p_T as well as on pseudorapidity η, coming from geometrical effects or detector response, must be minimized in all the algorithms. Trigger efficiency measurement from data will be done with the "Tag and Probe" method, when possible. It's based on the selection of a clean signal sample, as for example Z bosons, Y or J/ψ to leptons. One of the lepton is selected as the trigger of the event, the so-called tag lepton, while a second offline track defines the efficiency (probe) of the applied trigger selection. The method has been proved to be bias-free, since the fractional efficiency difference with respect to the quantities generated by the Monte Carlo is constant along the p_T spectra (see Fig. 1.b). The systematic uncertainties of the method are compared as well with simulation, while deep studies are ongoing on background contamination due to events containing multiple leptons that are not stemming from single particle decays.

Trigger commissioning

There have been many competing demands on the trigger system during the first phase of early running. The ATLAS commissioning went on a long phase of cosmic rays running, during which muon triggers were the main source of rate. It allowed the timing-in of the detectors, both trigger and readout, and provided the samples to test the main reconstruction slices and calibration centers. Cosmic ray runs and first experience with beams in September 2008 already gave an attempt of timing-in the level-1 triggers and validate the energy calibration, while testing HLT algorithms and architecture. A first scenario of low LHC start-up luminosity, up to $10^{31}\text{cm}^{-2}\text{s}^{-1}$, is under study on many aspects, again allowing detector and trigger commissioning while selecting Standard Model processes. At the time of writing this proceeding, the first-level trigger system has been tested for long time with cosmic rays and first beams in 2008. The readout chain has been tested at 80 kHz sustained rate. The High-level trigger has been deployed at 35% of the final system (850 nodes installed and working) and tested at 60 kHz. This configuration has been stressed with a $10^{31}\text{cm}^{-2}\text{s}^{-1}$ trigger menu with technical runs, during which simulated raw-data preloaded into the readout systems have been played back through the DAQ system. The finalization of the system will be luminosity driven: 500 level-2 nodes and 1800 event-filter nodes are expected (8 cores at 2.5 GHz and 2 GB Memory). The DAQ system has been routinely running since 2008, with the full dataflow infrastructure installed and working. Cosmic ray data are used to check timing and calibrate E_T thresholds, validating procedures done with test-pulses or radioactive sources. For HLT, more than 200 trigger items have been tested online, validated the level-2 processing time (40 ms) and verified that acceptance and rejection power for each algorithm is consistent with offline running. As an example, the level-2 tracking efficiency is shown in Fig. 2.a.

First beams in ATLAS. On 10th September 2008, first beams passed around LHC in both directions. At first step, the beams were brought around the machine and stopped on collimators, upstream of ATLAS. Bunches of 3-5$\times 10^9$ protons at 450 GeV energy produced a large number of secondary particles traversing the experiment, the so-called beam splash events. ATLAS was ready to detect and record these events. They were useful as crucial tests of the level-1 trigger: first for the systems mainly designed to detect the beam activity (Beam Pick-up Timing Experiment, BPTX, and Minimum Bias Trigger Scintillators) and then to correct the relative timing among all the systems, where a large fraction of the readout channels fired. The first beam events were recorded with triggers already tested, as for example the calorimeter trigger, before the local beam instrumentation has been setup. The BPTX provides a stable time reference for all the systems which then could be aligned for subsequent beams. The timing calibration of the level-1 trigger system was performed in two days, with all the detectors working on adjusting the trigger and the readout in parallel (Fig. 2.b). Even if precise timing adjustments will need collision data, with circulating beams downstream timing is similar to that of collisions and the remaining adjustments continued after the beam stopped using cosmic events.

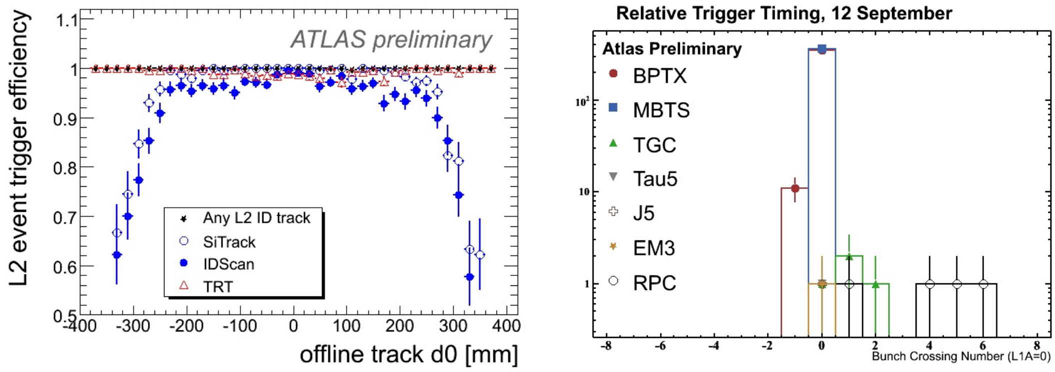

FIGURE 2. Left (a): Level-2 tracking efficiency as a function of track impact parameter with different algorithms. Right (b): Timing distribution of Level 1 triggers from September 12 2008, the third day of single-beam data. Events were triggered here with the MBTS at BC 0. Of note in this plot is the excellent timing of the BPTX and MBTS, and also the relatively small coincidence of the minimum bias trigger with calorimeter and muon triggers. The latter point implies that the beam quality had improved significantly in the first 48 hours of beam time. The timing of the RPC had not been tuned at all prior to this run.

Trigger strategy

The target output rate of the trigger system has been set to 200 Hz, given the average 1.6 MB event size (related to the 10^8 detector readout channels) and the maximum storage through-put of around 300 Mb/s. The trigger rate allocation on each trigger item is decided within the trigger menu, and is based on: 1) physics goals, plus calibration and monitoring samples; 2) required efficiency and background rejection; 3) the corresponding consuming bandwidth. Expected trigger rates are calculated from large samples of simulated data, including large cross-section backgrounds (minimum-bias and QCD events). Large uncertainties are expected due to detector response and jet cross-sections knowledge, that must be tuned with early data. The largest source of muon triggers are from b/c quarks and π/K in-fight decays. For E/p and jet calibration, the trigger has to guarantee the Standard Model channels as W, Z, Y, J/ψ and Drell-Yan direct-γ production. The respective trigger rates can be adjusted by applying prescale factors such that calibration triggers do not interfere with the physics triggers. At the start-up luminosity, $10^{31}\text{cm}^{-2}\text{s}^{-1}$, the selection strategy is focused on low thresholds and loose selection criteria, while taking HLT in pass-through mode for offline validation at the very beginning. A maximum of 256 level-1 trigger items, which are combination of one or more level-1 trigger inputs, can be deployed at any time. Different pre-scale factors can be applied on each item to tune the rates as luminosity varies during a fill, if necessary. As luminosity grows up, higher level-1 thresholds and multi-objects triggers will be deployed for validation and rate control, while the HLT will start the commissioning applying low thresholds. The start-up trigger menu contains about 130 level-1 items and 180 HLT selection chains. All calorimeter and muon triggers are non-prescaled, except the low single electromagnetic threshold at 3 GeV.

Concluding remarks

ATLAS is preparing the commissioning with beams that will arrive in November 2009. Considerable progress has been made in a short period with single beams activity last year, with first steps for timing-in and much useful experience gained in understand the system. The trigger and daq system fulfills all its requirements and is ready for data taking. It can be expanded according to needs with increasing luminosity and plays a central role in the rich physics program of ATLAS. Hereto, much effort was put to ensure flexibility of the trigger system and ability to react quickly at different detector and machine performance.

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